Frequency Tunning of THz Wireless Signal By using Optically Phase Locked Loop System

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***Abstract*—We experimentally demonstrate, for the first time, the photonic generation of a continuous tunable THz wireless signal based on using optical phase locked loop (OPLL) sub-system and optical frequency comb (OFC). The OPLL is employed to select one optical tone out of optical comb and shift it by desired frequency offset allowing for the frequency tuneability of THz carrier signal. The selected optical tone from OPLL is heterodyned mixed with another selected optical tone of the optical comb to generate a stabilized THz frequency carrier with a low phase noise. The proposed setup is demonstrated by transmitting wirelessly a THz signal modulated with 10 Gbaud QPSK filtered with square root raised cosine (SRRC) at 0.1 roll off factor. The system performance is evaluated for four tuned THz carrier frequencies by changing the wavelength of the laser included in the OPLL. This configuration is a promising architecture that would allow a THz carrier to be flexibly generated at the central office with high frequency stability and low phase noise.**

Keywords— Photonic THz generation; optical phase locked loop (OPLL); optical heterodyning; digital coherent detection; high-speed wireless; fibre wireless; radio-over-fibre.

I. Introduction L

THz wireless communication in the frequency band (0.1 – 1 THz) has attracted a lot of interests from researchers and industry sectors globally [1]. This is due to the huge bandwidth available that can enable future ultra-boradband wireless communication, and helps to overcome the spectrum scarcity and capacity limitation of the current wireless networks. Many works were previously reported for utilizing this band and to achieve data rate with capacity >100 Gb/s using advanced modulation format and multiple wireless channels [2], [3]. However, most of these works generate the THz signal heterodyne mixing of two free running lasers. Those lasers exhibit frequency fluctuations and phase noise that translated onto the generated THz carrier which can reduce the signal quality and impair the system performance. Therefore, this would require the use of expensive lasers with narrow linewidth, and the implementation of complex digital signal processing (DSP) algorithms at the receiver to remove the frequency offset and compensate for the phase noise on the modulated signal. Despite the advanced development of DSP codes, DSP processing is difficult and limited by the laser's linewidth, and consumes energy and increases latency.

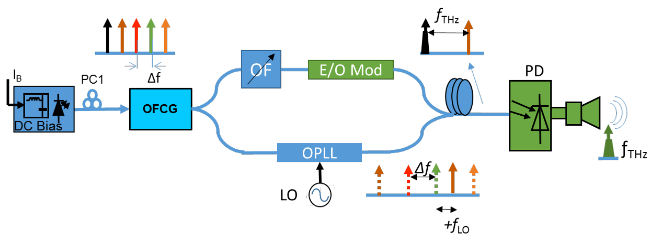

Fig. 1. Block diagram of photonic generation of frequency tunable THz signal.

Other reported works showed the generation of high spectral purity THz signal can be produced by using an optical frequency comb (OFC), where two phase correlated optical tones can be selected from the same laser. This technique showed an improved performance over the two free running lasers, and reduce the complex computation at the DSP in the receiver [4]. Despite this, some phase instabilities was seen in the OFC based scheme caused by the refractive index changes due to temperature and acoustic noise in the two optical fiber paths. In order to remove the phase instability, a phase stabilizer with optoelectronic feedback control can be inserted to achieve a real-time error-free transmission [5], [6]. An alternative approach showed phase stabilization achieved by using injection locking of two monolithic integrated laser diodes with OFC [7]. This was demonstrated for error free transmission of 10 Gb/s OOK at W-band. However, those schemes are based on OFC tones spacing which imposes some constrains on a carrier frequency and its tuneability.

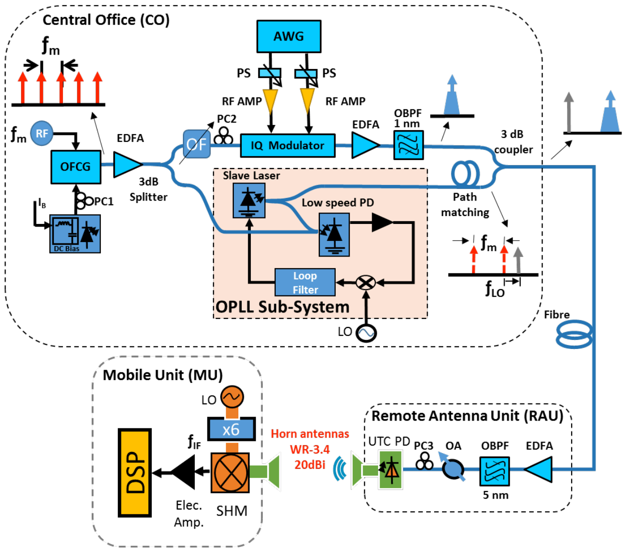

Fig. 2. Schematic diagram of the experimental setup for the tunable THz frequency.

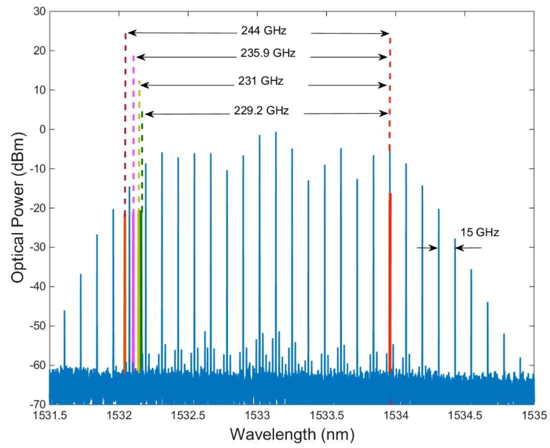

Fig. 3. Optical spectrum of the optical frequency comb and the selected optical tones from the OPLL.

A heterodyne optical phase locked loop (OPLL) is a well-known technique allow the phase of the slave laser to be stabilized to an incoming optical reference by providing feedback control to the current of the slave laser and with additional frequency offset defined by an external reference synthesizer.. Homodyne detection at 40 Gbps was demonstrated using a Costas loop as OPLL in [8]. Also, it has been reported using phase locked loop in demonstrating millimeter wave at 60 GHz for RoF system [9].

In this paper, we demonstrate the photonic generation of a frequency tunable 10 Gbaud quadrature phase shift keying (QPSK) THz wireless signal using OFC combined with an OPLL system. Fig. 1 shows the block diagrams of the proposed THz wireless-over-fiber system with a tunable carrier frequency between 229 GHz and 244 GHz. A single wavelength laser is used to generate phase correlated optical tones in an optical frequency comb generator (OFCG) based on electro-optic modulation, where the comb line spacing is defined by driving RF frequency. These optical tones are split into two optical paths. One path is filtered to select one of the optical lines to be data modulated in electro-optic modulator. The second optical path is injected into an OPLL sub-system for generating an optical local oscillator (LO) spaced by desired THz frequency. The OPLL, here, is used to obtain a tuned optical LO by adjusting the wavelength of the slave laser and fine control of the electronic LO. This configuration would give more flexibility to adjust the carrier frequency of the THz transmitter in the central office. The slave laser included in the OPLL can be tuned across 8 nm (1 THz) range and the frequency offset between 4 GHz and 12 GHz has been demonstrated [10]. The system performance is evaluated for four different THz frequencies obtained by adjusting the OPLL offset.

II. Experimental Setup and Results

Fig. 2 shows a proposed schematic diagram of the experimental setup for evaluating THz signal with 10 Gbaud QPSK modulation. It consists of the central office (CO), remote antenna unit (RAU), and mobile unit (MU). Inside the CO, the OPLL is implemented to control the offset frequency and phase locking to one of the OFC lines.

A. *THz Transmitter Setup*

The CO setup contains a continuous wave (CW) light source at 1533.14 nm with a linewidth of 10 kHz. The CW source was injected into an OFCG to generate multiple optical tones which are phase correlated and spaced by the frequency (f_m) of the RF signal applied to the OFCG. The frequency comb source is mainly based on driving a dual drive Mach-Zehnder modulator (DD-MZM) by 15 GHz, as in [11]. Then, the optical comb signal was optically amplified by an erbium doped amplifier (EDFA) into 17 dBm before split them to two branches using a 3 dB optical coupler. The upper branch has an optical bandpass filter (OBPF) to select one of the optical tones before it was modulated in an IQ data modulator. The modulated signal was 10 Gbaud QPSK at the baseband, filtered by a square-root raised cosine filter (SRRC) with a roll off factor of 0.1. This was generated using Matlab codes offline and then uploaded into an arbitrary waveform generator (AWG) with sampling rate of 50 GSamples/sec. The output of the IQ modulator was optical amplified and filtered by a 1 nm OBPF to remove out-of-band amplified spontaneous emission (ASE). The lower optical branch was inserted into an OPLL sub-system, to filter out one of the optical tone of OFC lines and tune it to the precisely defined offset frequency. The output of OPLL is phase correlated to the injected optical comb lines. Then, the modulated optical signal and the tuned optical tone are combined in a 3 dB coupler before being transmitted to the remote antenna unit (RAU). An additional fiber length was added after OPLL sub-system to match the delay difference between the two arms. The combined optical signal is then optically amplified and filtered with OBPF of 5 nm bandwidth before heterodyne detection with an unpackaged uni-traveling carrier photodiode (UTC- PD) with an integrated coplanar waveguide (CPW) output to generate the sub-THz modulated signal. The output of the photodiode was coupled to a 20 dBi horn antenna (WR-3.4) using a coplanar millimetre-wave probe.

B. *Optical Phase Locked Loop (OPLL) Sub System*

The OPLL setup consists of a monolithic photonic integrated chip (PIC) and commercially available electronic feedback loop used to control the frequency and the phase of the slave laser, as illustrated in Fig. 2. The OPLL PIC is based on InP and consists of a distributed Bragg reflector (DBR) laser, and low speed photodiode among other components [10]. In the OPLL sub-system, the signal from OFCG is heterodyned mixed with the slave laser on an integrated low speed photodiode (12 GHz bandwidth at -6 dB) and consequently compared with RF local oscillator on the phase detector. This results in the baseband phase error signal, which is used to adjust the phase of the slave laser. The frequency of the slave laser is offset from the closest optical tone by any frequency between 4 GHz and 12 GHz and is precisely defined by the electrical local oscillator. This offset frequency range is limited by the bandwidth of the photodiode in the OPLL PIC and the other electric components used in the short delay electronic feedback loop circuit [10]. Even thought, the continuous tuneability of the offset frequency can be achieved up to 12 GHz in the OPLL sub–system the maximum offset frequency required equals the half of the frequency spacing between the comb lines. The instability of locking the slave laser will occur if the offset frequency falls exactly in middle between the comb lines [12]. In our case, the frequency comb lines are spaced by 15 GHz. So, the frequency offset can be tuned from 4 GHz to around 7.5 GHz. In this experiment, the wavelength of the slave laser was set to be close to the one of the optical tones spaced by 15 optical comb lines (225 GHz) from the other selected optical tone. Then, by controlling the electrical LO of the OPLL at 4.2, and 6.0 GHz, we were able to tune the generated THz carrier for 229.2 GHz, and 231 GHz, respectively. Then, to tune for higher frequencies at 235.9 GHz and 244 GHz, the wavelength of slave laser is adjusted to be close to the lower and upper side of the optical tone spaced by 16 optical lines (240 GHz) from the optical modulated signal. Then, the electrical LO of the OPLL is set to 4.1 and 4.0 to tune the THz carrier for 235.9 GHz, and 244 GHz, respectively. Fig. 3 shows the optical spectrum for optical comb source, and the four tuned optical tones using the OPLL.

C. *THz Receiver and DSP Processing*

The modulated THz signal propagated over a wireless channel to the mobile unit (MU) where it was received with a 20 dBi horn antenna. At the MU, the received THz signal was initially downconverted into intermediate frequency (IF) by mixing it with the 6^{th} harmonic from LO signal using a sub-harmonic mixer (SHM). After that, the IF signal was amplified by an RF amplifier and then recorded with a real time scope (RTS) for digital signal processing (DSP) whose sampling rate and bandwidth were 80 GSample/s and 36 GHz, respectively. The recorded signal length was 10 μsec which corresponds to 200,000 bits. The digitized signal was processed offline using DSP blocks implemented in Matlab. First, it was digitally downconverted to the baseband using the nominal value of the IF, and filtered by SRRC of 0.1 roll off factor. Then, the digitized filtered IQ baseband signals were resampled, channel equalized based on blind method using the constant modulus algorithm (CMA), and carrier phase estimation (CPE) based on the fourth power Viterbi-Viterbi algorithm. After elimination of the π/2 phase ambiguity, the bit error ratio (BER) was calculated by counting the number of errors in the received bit stream.

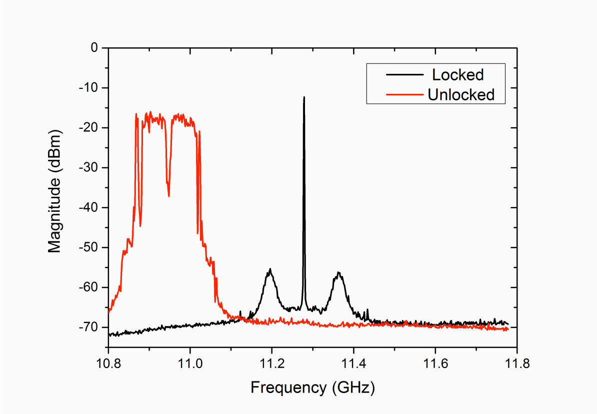

Fig. 4. Electric spectra of THz carrier, after downconversion to IF frequency, for the locked and unlocked operation of the OPLL. Measured at RBW= 300 kHz, VBW= 100 kHz, SWT= 840 ms for 20 seconds max hold.

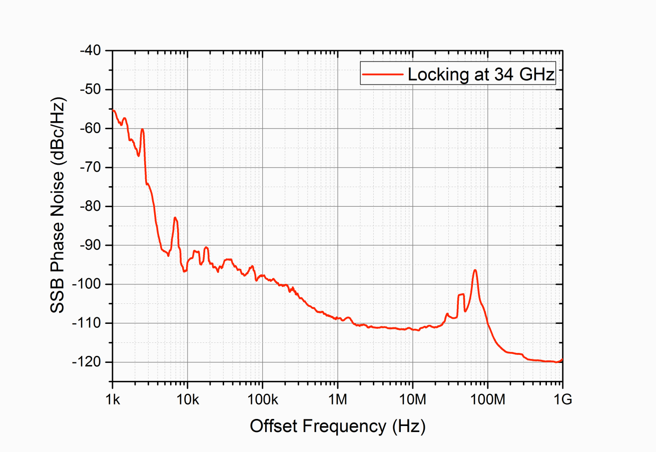

Fig. 5. Phase noise measurement of the heterodyne mixing between OPLL output and optical carrier spaced at 34 GHz.

D. *Results and Discussions*

Without any signal modulation, Fig. 4 shows the electrical spectra of the heterodyned mixing of the selected optical carrier and OPLL output spaced by 229.5 GHz and downconverted to IF frequency. The measured spectra were obtained for 20 seconds using a max hold function. In the case of free running laser, the generated carrier fluctuates in frequency within the range of ~ 200 MHz. These fluctuations are caused mainly by the thermal instability of the two lasers. This would require an implementation of frequency tracking in the receiver. However, an improved spectrum with stabilized frequency was obtained when the OPLL was active. An increase in power was also observed in the electrical carrier. The secondary peaks around the carrier were 48 dB lower than the carrier power, and indicate the bandwidth of the OPLL. As it can be seen within the loop bandwidth, the phase noise of the carrier is controlled and kept low. Furthermore, to evaluate the quality of locking, the phase noise was measured for a heterodyned mixing of the OPLL output with an optical carrier spaced at 34 GHz as shown in Fig 5. The observed phase noise

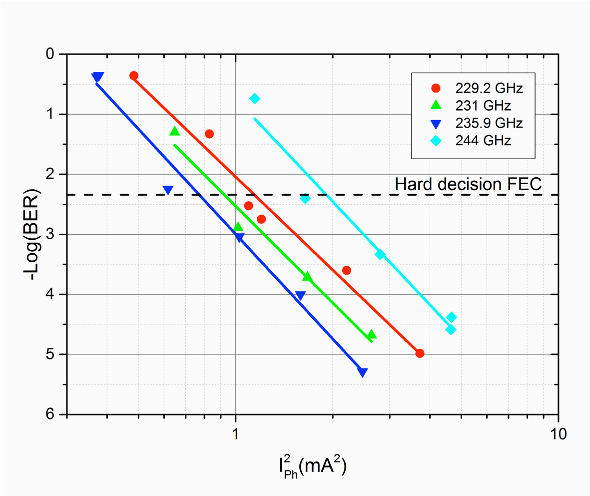

Fig. 6. BER as a function of photocurrent squared for the four tuned THz signal.

at 10 kHz offset from the carrier was -95 dBc/Hz also we notice the peak noise for loop bandwidth occurs at 80 MHz.

The transmission experiment of 10 Gbaud QPSK THz wireless over fiber was performed, with the OPLL was tuned to give four THz carriers of 229.2, 231, 235.9, and 244 GHz. Fig. 6 shows the four BER measurements for each of the tuned frequencies. It has to be noted here that, the DSP processing was reduced by eliminating the frequency offset algorithm, and minimizing the block length averaging in phase noise compensating algorithm. All plots have the same slopes and reach below the BER limit of 3.8×10^{-3} hard decision forward error correction. The small penalty seen in the BER measurements was due to the unflattened frequency response of the RAU which results in a change of the transmitted THz power [2].

III. CONCLUSIONS

We have successfully experimentally demonstrated the photonic generation of semi-continuous tunable THz signals based on OFCG and heterodyne OPLL. The demonstrated system performs the tuning of the THz carrier with a frequency offset and phase locking to the one of the optical comb lines. The results showed an improved frequency stability and phase noise of the THz carrier compared to using two free running lasers. This allows reduced DSP processing delay, and power dissipation at the receiver end. The proposed system configuration is a potential solution for accurate, arbitrary THz carrier frequency generation in the CO. This can also give more flexibility for distributing THz signals to multiple RAUs.

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